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Effects of Drilling Fluids on Reef Corals: A Review

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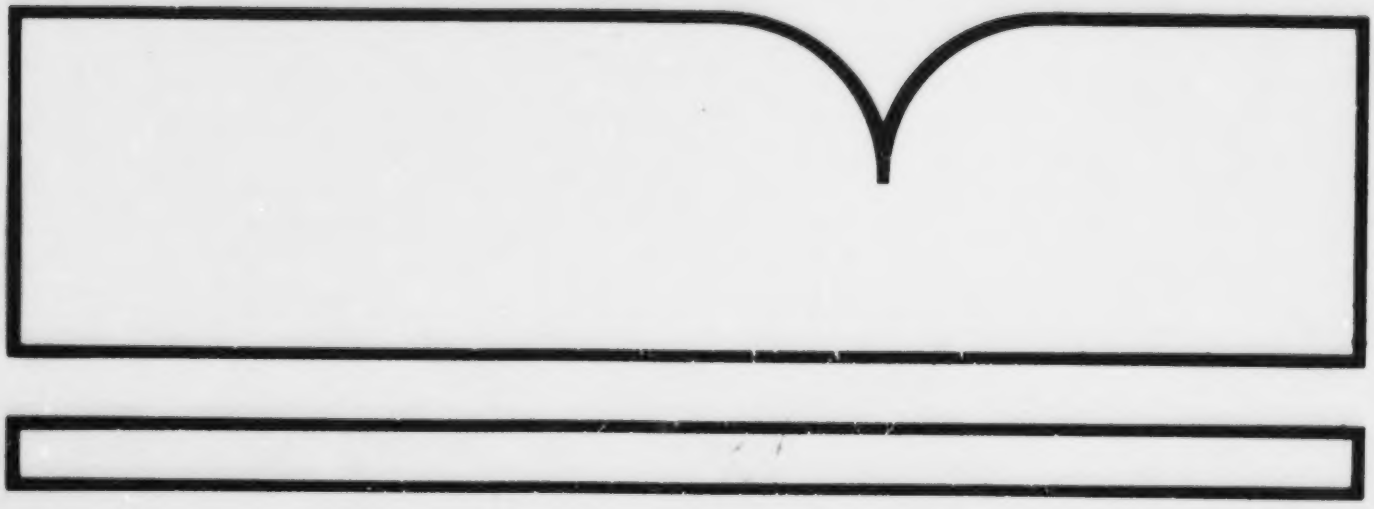

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CHAPTER __

EFFECTS OF DRILLING FLUIDS ON REEF CORALS: A REVIEW

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ABSTRACT

This chapter reviews research on the effects of drilling mud on coral reef communities, concentrating on the major reef fauna: the reef-building or hermatypic corals. Drilling mud is an effluent introduced to the marine environment in large quantities during a typical offshore drilling operation. Concern over its possible detrimental effects, when drilling activities are near coral reefs, has been the impetus for the work to be discussed. The topic is of recent origin; until 1977, there were no literature reports of drilling mud - coral studies.

Experiments have shown that burial of corals in drilling mud caused mortality and that certain drilling muds applied as slurries could not be removed by corals. Under field conditions, however, slurries were removed with the assistance of natural currents, but appeared to cause lowered growth in treated specimens. In other experiments, certain species showed behavioral stress symptoms after 96 h exposure to 0.100 ml l^{-1} drilling mud and exposure to 1.000 ml l^{-1} caused mortality in 65 h for three of seven species tested. A separate laboratory study indicated that chronic (6 wk) exposure to 0.100 ml l^{-1} drilling mud caused a 85% decrease in calcification, a 35% decrease in respiration, a decrease in zooxanthellae content, reductions in gross photosynthesis, NO_3^- uptake, NO_4^+ uptake, and feeding, as well as some death. Average linear skeletal growth also

decreased. A field assessment of a reef, several years after impact by drilling, indicated a 70-90% reduction in foliose, branching, and plate-like corals within a 115 by 85 m ellipse around the drill site. This reduction was postulated to have been caused primarily by sedimentation and burial effects of cuttings discharge.

Drilling mud composition varies with depth of drilling and characteristics of the substrate. It is introduced into the sea at variable rates and for varying durations. The distribution of the mud is subsequently affected by currents and depth of discharge. Some studies of concentration of drilling mud downstream from a drilling operation have been completed. Results are variable depending upon the above factors. In general, they indicate that detrimental effects on corals, as extrapolated from the limited information on effects, seem probable within a minimum of 100 m distance from the source.

Research has only begun to systematically evaluate the effects of drilling on coral reef communities. Future efforts must include: (1) an understanding of the bioactive constituents of drilling fluids; (2) dispersal patterns of muds discharged from rigs, including particulate and soluble fractions; (3) the long-term effects and the ability of corals to recover from intermittent and chronic exposure to toxic concentrations of drilling mud; and (4) effects of drilling muds on other members of the reef ecosystem, including bioaccumulation of toxic components by edible species.

1. INTRODUCTION

Coral reefs are among the most diverse and productive of ecosystems (Lewis, 1977). They assume economic importance because of the fisheries and tourism they support and their natural function in shoreline protection.

The basic structure of coral reefs is provided by the hermatypic or reef-building corals. Damage to or degradation of these organisms can result in a complete "collapse of the complex community of organisms, which live in close associate with the corals" (Loya and Rinkevich, 1980). Concern over the detrimental effects on coral reef communities has been focused on the effects of natural disasters such as Acanthaster infestations (Endean, 1973), bacterial and algal diseases (Garrett and Ducklow, 1975), and hurricanes (Stoddart, 1971; Connell, 1978; Woodley et al., 1981), and of man-made disturbances such as sedimentation and turbidity from dredging and mining (Levin, 1971; Dodge and Vaisnys, 1977; Bak, 1978; Ditlev, 1978), thermal stress from power plant effluent (Jokiel and Coles, 1974), and oil pollution (see review by Johannes, 1975 and Loya and Rinkevich, 1980).

A problem, which until recently has received little attention, is that of the effects of drilling activities on or near coral reefs. Increasing need for new supplies of oil and natural gas have led to an explosive growth in offshore drilling. Drilling activities are planned or already in progress in the northern Gulf of Mexico at

the Flower Garden Banks, the western Atlantic at the Marquesas Keys, the Caribbean at Trinidad and Saba, the South China Sea near Malaysia and the Philippines, and the Arabian Gulf, often near or on coral reef communities.

In addition to the danger of oil spills, potentially detrimental effects of drilling near coral reefs include the actual physical disturbances caused by anchoring, pipeline and drill rig construction, the resuspension of bottom sediment created by such activities, shadowing by the rig platform, and the discharge of drilling effluents which include "sewage, deck drainage, produced formation water, produced sand, drilling muds, drill cuttings, and well-treatment materials" (Thompson and Bright, 1977). Of these, a major concern is the discharge of used drilling mud, which is a highly specialized fluid necessary for the drilling process. This material serves "to remove drill cuttings, maintain hydrostatic pressure, prevent pipe corrosion, and cool and lubricate the drill bit. To meet this variety of specific requirements, these fluids may consist of pH and ion-control substances ($NaOH_3$, $NaHCO_3$), gelling and suspending agents (clay minerals and acryllic polymers), deflocculants and filtration control substances (ferrochrome lignosulfonate, sodium acid pyrophosphate), fuel oil, defoaming agents (aluminum stearate), and weighting agents (barite)." (Trefry et al., 1981). Barium, in the form of $BaS0_4$, is the main ingredient for weighting material and often represents more than 15% of the drilling fluid

mass (McGlothin and Krause, 1980). Ferrochrome lignosulfonate (FCLS) accounts for high Cr concentrations in the mud. Other trace elements such as Pb and Zn are potential contaminants (Chapter , Trefry et al.). It has been estimated by the U.S. Bureau of Land Management that a well 3,200 m deep may produce 690 tons of cuttings and let escape 23 tons of drilling mud into the marine environment (Thompson and Bright, 1977).

Because of the potentially toxic nature of drilling mud, drilling activities near coral reefs have been viewed as environmentally hazardous by many of those involved with maintaining, protecting, and managing this resource. Studies of effects of drilling mud are scarce and are filled with qualitative as well as quantitative observations. Many of the existing studies have been part of programs aimed at assessing the potential impacts and effects of drilling activities in the western Gulf of Mexico on corals of the Flower Garden Reefs. "Reserves of natural gas underly this region, and hydrocarbon activities were initiated in 1975. Some nearby tracts are actually in the production phase, and the area immediately around the Banks is or will soon be subject to intensive exploration activity." (Spiller and Rieser, 1981).

The task of assessing effects of drilling mud is complicated by a number of factors. Data on concentrations or levels to be expected from a single drilling operation generally have been

unavailable. How concentrations will vary from a single exploratory well to multiple simultaneous production operations is not known. A major concern in interpretation of drilling mud effects on corals is drilling mud composition, which varies according to well depth and substrate characteristics. Consequently, at certain times during drilling, effluent may be more or less toxic. It is often difficult to replicate drilling mud composition in laboratory testing and nearly impossible to replicate used mud characteristics. Thus the researcher is forced to obtain supplies from a well in progress and to rely on well logs for a list of drilling mud components. Alternatively, he is free to make his own recipe; however, potential chemical changes induced in used mud may be overlooked.

This chapter will attempt to review our present state of knowledge on the effects of drilling mud on reef corals. The discussion will be limited to effects on corals, partly because of the importance of these animals to the reef ecosystem, and partly because of the lack of information on other faunal groups inhabiting coral reefs.

We first consider the available information on the effects of various concentrations of drilling mud. Relying on other available information about drilling mud concentrations that occur in the environment, we advance some predictions about the possible impact of this pollutant on coral reefs. Finally, we briefly discuss needed research which will eventually help to formulate management decisions.

2. LITERATURE REVIEW

2.1 Burial-Sedimentation

Adult corals are sessile and experience their environment from a fixed point with no possibility of movement to avoid disturbances. Coral reefs flourish in areas of low natural sedimentation and where water motion is strong enough to remove most fine sediment particles.

In the drilling mud literature there is no clearcut separation between effects due to sedimentation alone versus those caused by potentially toxic chemical constituents, or due to a synergism between the two. In the following discussion we treat research dealing with burial and clearing rates loosely under the grouping of sedimentation, realizing that there may be additional contributing factors.

It is well known that although most corals can withstand low rates of sedimentation, high rates of sedimentation are lethal (Marshall and Orr, 1931; Mayer, 1918; Edmondson, 1928). Most species have a limited ability to remove sediment that has fallen on their surfaces, primarily by coenosarc distension (polyp swelling), mucus entaglement, and ciliary action (Lasker, 1980). Yonge (1931) discussed sand clearing by Montastrea annularis. Hubbard and Pocock (1972) provide information on and ranking of the efficiency of various species at removing different size classes of sediment. Bak and Elgershuizen (1976) present

rates of removal of clean and oil-soaked sediment for various coral species.

Although a certain amount of sedimentation must be considered as a normal environmental parameter for reef-corals, high rates of sedimentation have been shown to promote lowered coral growth rates (Aller and Dodge, 1974; Dodge et al., 1974; Loya, 1976; Bak, 1978), which can result in death (Dodge and Vaisnys, 1977). Sediment removal requires energy expenditure that may detract from growth and from other important metabolic processes. In addition, increasing sedimentation also increases turbidity, which reduces the amount of light available to corals' zooxanthellae.

In a laboratory study Thompson and Bright (1977) compared the ability of three species of reef coral (Diploria strigosa, Montastrea annularis, and Montastra cavernosa) to clear layers of four sediment types from their surfaces. The four sediment types were: used whole drilling mud, barite, bentonite, and $CaCO_3$. The drilling mud contained, in addition to barite and bentonite, such additives as lime, lignite, ferrochrome lignosulfonate, aluminum stearate, and detergents, and was obtained after use from a well drilling at 2,591 to 3,094 m. Thompson and Bright poured 24 ml slurries evenly over the surfaces of the corals. Although the clearing rates varied among species, all 4 species effectively removed barite, bentonite, and $CaCO_3$ as

individual treatments; however, no species was able to remove the used whole drilling mud. They suggested that toxic soluable components of the whole mud were responsible for this difference.

In another laboratory study Thompson (1979) compared the ability of M. annularis specimens (3.8 cm diameter core plugs drilled from a single colony) to remove 10 ml aliquots of two different muds (muds "A" and "B") and natural fine-grained carbonate mud. Mud A was a freshwater FCLS mud, obtained from the mudpit of a platform located offshore of a Louisiana well drilling at 4,200 m. Mud B was similarly obtained from another platform offshore of Louisiana but drilling at 1,650 m. Two corals were used for each treatment. Twenty-six hours after application, one specimen had removed all of mud A, and the other had removed only 20%. The remaining mud was removed at this time, but the tissue that had been covered died three days later. Both corals covered with mud B were clear within two hours and both corals covered with natural carbonate mud were clear within four hours. Mud A was more concentrated than mud B and Thompson (1979) suggested that this may have been responsible for the difference in coral response.

Thompson (1979) conducted a further experiment by burying colonies of M. annularis and Porites astreoides in carbonate sand and in drilling mud (mud "A") for eight hours. He reported that

after 15 h specimens of M. annularis treated with sand had lost all of their zooxanthellae but were alive, whereas those buried in drilling mud were dead. All of the colonies of P. aseroides that had been buried in drilling mud died within ten days but those buried in the sand appeared to recover completely.

Thompson's (1979) experiments were done in aquaria with limited water motion and using concentrations of drilling mud that would only be approached in the field very close to the discharge point. He also observed clearing rates in the field where water motion would be expected to accelerate sediment removal. A 5 ml slurry of mud "A" was applied to four heads of M. annularis and a similar amount of carbonate sand was applied to four others. Two hours after treatment, all corals were greater than 95% free of sediment. Later observations revealed no mortality or zooxanthellae loss; however, mesenterial filiments were extruded on all heads. Clearly, natural water motion is an important factor in clearing corals of sediment and may act to decrease exposure time and detrimental effects of drilling muds.

Hudson et al. (1982) evaluated coral coverage at a Philippine reef impacted by two offshore drilling events. They reported a 70-90% reduction in foliose, branching, and plate-like corals within a 115-85 m ellipse around the two well heads which were located 3 m apart. Although an anchor chain scoured

an area 30 m to the west and northwest, the major coral mortality was postulated to have been caused by smothering from prolonged and localized buildup of cuttings. At present there is no cuttings pile in evidence. This was apparently removed by storm conditions that occurred after drilling. It seems possible that drilling mud associated with the previously existing cuttings pile may also have been responsible for at least some of the coral mortality.

2.2 Behavior

Individual coral polyps can alternate between the expanded and retracted state. Some species remain expanded much of the time, under favorable conditions, whereas other species have diel cycles of expansion (Sweeney, 1976; Sebens and De Riemer, 1977).

Events that act to disrupt this behavior or promote greater retraction may be viewed as stressful. Abrupt polyp retraction to drilling mud may prevent its uptake and thus be an avoidance response; however, long periods of retraction must interfere with food capture, sediment removal, and possibly photosynthetic activity. Coral polyp retraction, as a bioassay technique, is a useful and direct indication for measuring coral behavior. Two studies have used this method to examine the effects of various concentrations of drilling mud.

Thompson and Bright (1980) experimentally exposed seven species of reef coral (Dichocoenia stokesii, M. annularis,

Agarcicia agaricites, Acropora cervicornis, Porites furcata, Porites astreoides, and Porites divaricata) to three concentrations (0.100, 0.316, and 1.000 ml l^{-1}) of drilling mud for 96 hours. The mud was an unused, freshwater combination containing barite, bentonite, and ferrochrome lignosulfonate; it had been formulated for drilling at 4,200 m. This mud is apparently equivalent to mud "A" of Thompson (1979). The experiments were conducted underwater in closed aquaria with recirculating pumps on the reef flat of Carysfort reef in the Florida Keys. Corals were periodically observed or photographed to determine the degree of polyp retraction. Five species (M. annularis, A. agaricites, A. cervicornis, P. furcata, and P. asteroides) exhibited a higher than normal degree of polyp retraction during exposure to 0.100 ml l^{-1} and higher concentrations of drill mud. P. divaricata showed significant retraction at about 0.316 ml l^{-1}; however, D. stokesii did not react to any concentration. Specimens of M. annularis, A. agaricites, and A. cervicornis died within 65 h of exposure to 1.000 ml l^{-1} (although A. cervicornis did survive this concentration in another experiment). Thus, even at the very high concentrations of 1.000 ml l^{-1}, at least four of the seven species tested survived for 96 h. Long-term sublethal effects or mortality after cessation of drilling mud exposure, however, were not investigated.

In a second set of experiments, Thompson (1980) compared the

effects of two different drilling muds and of FCLS on the retraction behavior of specimens of Madracis mirabilis and M. decactis collected from the Texas Flower Gardens. Branches of these corals were exposed, in a flow-through system, to concentrations of 0, 0.001, 0.010, or 0.100 ml l^{-1} of mud or FCLS alone for up to four weeks. The first mud tested was from an Amoco exploratory platform drilling at 4,360 m; it contained only small amounts of FCLS, and did not cause any behavioral reactions at any of the concentrations tested over the three-week exposure period. The second mud, which was collected on 6 June 1979 from a Mobil Oil Co. Mobile Bay barge rig, was a fresh water lignosulfonate mud sampled when the well was about 4,500 m deep. Results indicated significantly reduced polyp expansion at all concentrations tested after only one day of exposure (Fig. 1). Thompson (1980) noted that this mud was not meant for discharge and may have had components that increased its toxicity.

In the experiment with FCLS alone, exposure to 0.100 ml l^{-1} caused most polyps to retract within 1.6 h, and all polyps to permanently retract after 19 h. All of these corals died by 5 d of exposure, exhibiting the "shut-down" reaction described by Antonius (1977). Exposure to 0.01 ml l^{-1} FCLS caused a significant increase in polyp retraction, but no coral deaths over the 29 d experiment. There were no statistically significant differ-

ences between the control and 0.001 ml l^{-1} FCLS exposed corals (Fig. 2).

Alteration of feeding behavior has also been used as an indicator of the effect of drilling mud on corals. Corals and other coelenterates have been shown to exhibit specific tentacle movement and mouth-opening patterns in response to crustacean body fluids and to isolated amino acids (Lenhoff, 1968; Mariscal, 1971). Since expansion-retraction behavior is affected by drilling mud, it is reasonable to assume that feeding behavior may be as well.

The response of polyps of M. annularis to brine shrimp extract after prior exposure to 0, 0.001, 0.010, and 0.100 ml l^{-1} drilling mud for six weeks was examined by Szmant-Froelich et al. (1981). All exposure groups showed normal response except for the 0.100 ml l^{-1} corals which no longer expanded or showed a feeding response when placed in clean seawater. Exposure was then terminated and the corals were maintained in clean flowing seawater for one week during which their response to the shrimp extract was tested twice daily. No recovery of full feeding behavior was seen among the 0.100 ml l^{-1} corals. The corals were next tested for their response to various concentrations of L-proline, ranging from 10^{-2} to 10^{-9} M. L-proline was chosen because it is the most effective amino acid in stimulating feeding behavior in Montastrea cavernosa (Lehman and Porter, 1973). The controls

exhibited mouth-opening behavior at concentrations above 10^{-5} M, but none of the drilling mud exposed corals responded to any of the concentrations of the test solutions (N. Richards, personal communication). It is not clear why the 0.001 and 0.010 ml l^{-1} corals responded to the brine shrimp extract but not to the proline alone. It seems unlikely that L-proline underwent reaction with a drilling mud constituent that renders it undetectable to the corals. These experiments were conducted in clean seawater after prior drilling mud exposure. The results are suggestive of some disruption of feeding behavior even of corals previously exposed to 0.001 ml l^{-1} drilling mud.

2.3 Physiological

Various physiological functions have been used to determine the sublethal effects of chronic exposure to drilling mud on corals. Krone and Biggs (1980) measured respiration and ammonium excretion rates of fingers of Madracis decactis exposed to 0.100 ml l^{-1} drilling mud (Mobile Bay, no FCLS added) alone and with added FCLS (0.003 and 0.010 ml l^{-1} FCLS) over a 17 d exposure period. Although measurements were made in the light, illumination was too low for any net photosynthesis or ammonium uptake by the zooxanthellae. Because no dark measurements were reported, it is not possible to distinguish between the effects of the FCLS on respiration by the coral animals versus low-level photosysthesis by the algae. This

also applies for the ammonium excretion measurements. One coral of four in each of the FCLS treatments died within the first two weeks of exposure. Before death these two specimens had elevated oxygen consumption and ammonium excretion values; however, it is not clear whether the high values were due to elevated metabolic rates of the dying coral or to bacterial activity on the necrosing tissue. When these two specimens are deleted from the data analysis, there is no statistically significant difference in oxygen consumption or ammonium excretion between the different treatments. Visual observations indicated, however, that the FCLS-treated corals had a reduced degree of polyp expansion, which returned to normal within 48 h of return to clean seawater.

In a later study Szmant-Froelich et al. (1981) monitored respiration and calcification rates (animal functions) as well as ammonium uptake, nitrate uptake, and photosynthesis rates (algal functions) of M. annularis (eight replicates per treatment) exposed for six weeks to 0, 0.001, 0.010, and 0.100 ml l^{-1} drilling mud (from Jay oil field, Florida). New batches of mud were collected and used each week to simulate the changes in drilling mud composition that usually accompany increased drilling depth. Muds containing FCLS were introduced at the beginning of the third week of exposure, and muds containing diesel fuel at the beginning of the fourth week. A tabulated analysis of each mud may be found in Dodge (1982). No effects were seen in any of the functions measured until the fourth week of exposure, which

coincides with the introduction of the mud batch containing about 0.4% diesel fuel. After four weeks exposure, the specimens in 0.100 ml l^{-1} showed a 53% reduction in calcification, as measured by changes in total alkalinity, and a 25% reduction in respiration. These decreased further to 84 and 40% respectively, of control rates after six weeks of exposure. Gross photosynthesis was reduced by 26% after six weeks, nitrate uptake rates decreased by 42% and 28% after four and six weeks, and ammonium uptake decreased by 32 and 49% after five and six weeks. Calcification and respiration of corals in the 0.010 ml l^{-1} treatment were lower than but not significantly different from control values. All of the results are summarized in Fig. 3 a,b,c,d.

In order to determine whether the duration of exposure or the increased toxicity of the later muds was responsible for the depression of physiological function seen in the corals in the 0.100 ml l^{-1} treatment from the fourth week onward, a second series of two tests was conducted (Szmant-Froelich, personal communication) on samples of M. annularis. The first test used six replicates per treatment, collected from several neighboring colonies. The drilling mud used was the same as for the fifth and sixth weeks of exposure in the first experiment (Szmant-Froelich et al., 1981). The results showed a 55% decrease in calcification rate after only 24 h of exposure to 0.100 ml l^{-1} drilling mud, a lesser decrease in respiration rate after 3 d of exposure, and no significant effects on either gross photosynthesis or nutrient uptake after

five days. No effects were seen with 0.010 ml l^{-1} drilling mud. For the second test nine replicate M. annularis samples per treatment, collected from a single colony, were exposed to 0 and 0.100 ml l^{-1} drilling mud for three days. No detrimental effects attributable to drilling mud stress were observed in this test, indicating that individual corals may vary considerably in their susceptibility to toxic substances. The reason for the discrepancy between the results from the two different sets of M. annularis in this second experiment in unknown. It may be that the lack of prior exposure over four weeks to drilling mud (as in the first experiment) was a factor.

Branches of A. cervicornis (four replicates per treatment) were also exposed for 48 h to 0, 0.010, and 0.100 ml l^{-1} of the above drilling mud (Szmant-Froelich, personal communication). This species showed decreases in calcification rate of 50% and in nitrate uptake of 37% after only 12 h exposure to 0.100 ml l^{-1} drilling mud. Respiration and photosynthesis, however, were not affected during the 48 h exposure.

In a separate experiment E. Powell (personal communication) used ^{45}Ca uptake as a tracer for calcification rate in A. cervicornis, and found a 62% decrease in calcification rate at 0.25 ml l^{-1} and a 95% decrease at 0.500 ml l^{-1} after only 24 h of exposure, using Mobile Bay muds.

Results from these experiments suggest that calcification is

one of the first functions to be disrupted by drilling mud stress. Calcification rates are therefore valuable for monitoring at drilling sites for an early warning of detrimental effects. The results of these experiments also indicate there is variability of coral response to drilling mud among individuals of the same species, among species, and to drilling muds of different sources and composition. These experiments do not provide information on the precise cause of the various physiological effects (ie., from drilling mud exposure alone?, from a particular toxic component of the mud?, from reduced feeding response elicited by the mud?, etc.).

2.4 Linear Skeletal Growth

Growth rate should be a sensitive indicator of environmental stress because it reflects the end result of many physiological processes. Coral growth may be measured as the linear increment, or extension, of the calcareous skeleton. Calcification rates have been shown to be affected by exposure to drilling mud, and it is reasonable that linear growth rates would also be affected.

Hudson and Robbin (1980) conducted studies to assess possible effects of drilling mud on the growth of M. annularis. Specimens, in which eight per treatment were used, were collected, cemented onto cement tiles, and transplanted to a 3-m water depth on Carysfort reef, Florida, where a 2-4 mm thick layer of drilling mud was applied directly to their surface. This treatment was repeated four times at 2½-h intervals. A similar number of

specimens were untreated and used for controls. After treatment corals were allowed to grow undisturbed for six months. They were subsequently collected and skeletons were sectioned and X-radiographed to expose internal annual density banding. Linear growth of each coral over the six-month period was measured by reference to the last high-density band in the skeleton formed prior to the begining of the experiment.

Results suggested that treated corals grew less and at a more uniform rate than untreated ones. Testing of means (t-test) indicated a significant difference only at the 20% level, while testing of the variance (F-test) showed a significant difference at the 2% level. The authors tentatively concluded that high concentrations of drilling mud over a short period may not only reduce extension rate but also suppress growth variability. Variance, however, may be a function of the mean in which case the observed reduction could be an artifact of changes in the mean. On the other hand, it is worthwhile to note that the decreases in both mean and variability agree with coral extension rates measured on specimens from natural systems of high resuspension of bottom sediments (Dodge et al., 1974).

Barium analysis of pieces of these skeletons sampled from pre- and post-treatment growth areas showed normal values within the pre-treatment samples; whereas, several post-treatment samples contained highly elevated barium concentrations (Hudson and Robbin, 1980). The authors suggested that the high barium levels might be a

result of drilling mud material being trapped within sponge or other bored regions of the coral skeleton.

Dodge (1982) examined the linear growth rate of specimens of M. annularis exposed to 0, 0.001, 0.010, and 0.100 ml l^{-1} drilling mud (same experiment as the physiological measurements of Szmant-Froelich et al., 1981). Specimens were stained with alizarin red S prior to treatment, and growth was measured in sectioned skeletons as the linear increment from the stain reference line to the new skeletal surface. Selected measurements of polyp skeletal shape were also taken. Figure 4 is a sketch of a typical cross-section of the coral skeleton indicating skeletal structures and the presence and position of the stain line. Upward growth was measured as increases in septa length (SI), columella length (CI), and endotheca base (EBI) each normal to the pre-experiment endotheca length (OEL). These parameters declined significantly ($p < .01$) in the 0.100 ml l^{-1} treatment (Fig. 5). In addition the fossa length, an index of the relief of the coral skeleton, was measured in the pre-experiment and post-experiment skeleton for each treatment. The results showed a significantly depressed fossa in the 0.100 ml l^{-1} treatment.

Calical relief is an index of sediment removal ability among coral species (Hubbard and Pocock, 1972). It seems probable that this may be true to some extent within coral species as well. Foster (1980) found Jamaican M. annularis specimens from moderate sedimentation environments had greater

fossa length than individuals from sites of either high or low sedimentation. Fossa length is an index of vertical relief of the corallite. Effects which act to depress calical relief might also act to decrease a coral's ability for sediment removal. This might, at least temporarily, put the animal at a disadvantage for removing sediment, even after the event(s) which had originally promoted the changed skeletal morphology had ceased. If this is true and because corallites of this study showed a decreased fossa in the 0.100 ml l^{-1} drilling mud treatment, impaired sediment rejection capability of these corals may have been a result. Such an effect might lower the capacity of these coral for survival even after drilling mud stress had ended.

Natural in situ coral growth rates were evaluated by Hudson and Robbin (1980) on annual banding in core samples obtained from 12 massive M. annularis colonies living at 20 m depth on the East Flower Garden banks in the Gulf of Mexico. The purpose was to compare growth before and after 1974 when drilling activity was relatively nearby. A chronology of coral growth for the 12 corals was constructed by averaging annual linear growth of each coral by year. All 12 corals had records from 1970 to 1945, 10 corals dated back to 1921, and only two went back to 1887. The data indicated a growth rate from 1910 to 1957 of 0.89 cm y^{-1}; however, from 1957 to 1979 growth was depressed, averaging 0.72 cm y^{-1}. Skeletal samples from each coral were taken from the periods 1969-1974 and 1974-1979 and were analyzed for Ba and Cr

to assess possible chemical changes that might be related to nearby drilling activities that occured from 1974-1977. Concentrations were similar for both time periods and within the normal range reported for other corals from unaffected areas.

Dodge and Lang (1983) constructed a revised Flower Garden coral growth chronology using the data of Hudson and Robbin (1980) and dendrochronological techniques (Fritts, 1976). Each coral growth series was first converted to index values or percentages of mean coral growth rate. Then the 12 coral chronology was calculated by averaging the index values of each specimen by year (Fig. 6). The index growth chronology shows an overall declining trend from 1887 to the present, with a pronounced decline from 1957 to 1979. It does not seem likely that drilling activities were responsible for the observed growth changes because drilling only began in 1970's (Hudson and Robbin, 1980). The data does indicate, however, that some kind of environmental condition has promoted gradually declining growth since the 1890's with rather abrupt lowering since 1957.

One hypothesis is that this portion of the East Flower Garden Banks experienced a sinking due to salt dome collapse around 1957 (Rezak and Bright, 1981; Shinn, 1981) and lowered light levels at greater depth resulted in the abrupt decline in growth rates. Such a hypothesis is testable through collection of other specimens from nearby areas presumed or known to have been stable. Another hypothesis is that recorded environmental

data can explain the growth series. Dodge and Lang (1983) have found the coral growth series to be positively correlated with sea surface temperature and negatively correlated with discharge from the Mississippi and Atchafalaya Rivers (Fig. 6). It seems probable that secular water temperature fluctuations together with increasing river discharge (or climatic factors which influence discharge) are the major controls of Flower Garden coral growth.

Hudson et al. (1982) examined the extension growth histories of 38 Porites lutea specimens to reveal changes in annual extension, before, during, and after two drilling operations in an extensive live-coral bottom area off northwest Palawan Island, Philippines. Qualitative analysis of extension rates indicated that when compared to their pre-drilling averages and to rates of corals from a nearby control reef, little suppression of massive coral growth could be attributed to drilling. Mortality effects were observed, however, in foliose, branching, and plate-like corals as previously discussed.

2.5 Biochemical Composition

Biochemical measures have also been used to study the effects of drilling muds on corals. The biochemical composition of an animal reflects its nutritional and metabolic state. Corals that are behaviorally affected by muds in terms of expansion and feeding will become poorly nourished. Studies with

ahermatypic corals have shown that the nutritional states of corals were reflected in their overall biomass, their zooxanthellae content, and their lipid to protein ratio (Szmant-Froelich and Pilson, 1980).

These parameters were examined by Szmant-Froelich et al. (1981) in specimens of M. annularis. Table 1 presents the total nitrogen content (a measure of protein content), zooxanthellae density, and chlorophyll content of colonies after a six-week drilling mud exposure. The total nitrogen content of the 0.100 ml l^{-1} corals was about 8% lower than the controls; although the difference was not significant. The zooxanthellae densities in 0.100 ml l^{-1} corals, however, were 13% lower than the controls, a significant difference ($p < .05$). The chlorophyll content of the zooxanthellae remaining in the 0.100 ml l^{-1} corals was higher than that of the controls, possibly an adaptation to the lower light levels reaching the corals at this mud concentration. Changes were also evident in the lipid content [Chapter (White)]. Much of the change in lipid composition of the 0.100 ml l^{-1} corals may have been due to the decrease in their zooxanthellae density, since these algae have been shown to play a critical role in coral lipid synthesis and metabolism (Benson et al., 1978; Patton et al., 1977).

A study of E. Powell (personal communication) on A. cervicornis has shown dramatic decreases in the protein content

Tissue-N, Zooxanthellae Density and Chlorophyll Content of Montastrea annularis Exposed to Drilling Muds for Seven Weeks. Values are: Mean and Standard Deviations of eight pieces of coral.

Treatment	Tissue-Nitrogen N/cm^{-2} (μg mole N cm^{-2})	Zooxanthellae Density (x10 cells cm^{-2}	Chlorophyll *a* (μg cm^{-2})	Chlorophyll *a* (μg per 10^6 zooxanthellae)	Ratio of Chlorophyll *a* to chlorophyll *c*
Control, unfed	61 ± 16	4.6 ± 0.7	11.6 ± 2.3	2.5 ± 0.3	1.01 ± 0.08
Control, fed	67 ± 20	5.3 ± 1.5	17.2 ± 5.3	3.3 ± 0.7	1.31 ± 0.06
0.001 ml l^{-1}	66 ± 20	4.8 ± 1.2	14.0 ± 2.6	3.1 ± 0.8	1.23 ± 0.08
0.010 ml l^{-1}	67 ± 11	4.8 ± 1.1	15.2 ± 3.1	3.2 ± 0.6	1.29 ± 0.10
0.100 ml l^{-1}	56 ± 14	3.9 ± 0.2 *	14.6 ± 3.2	3.7 ± 0.8	1.34 ± 0.16

*This value significantly different from controls at $p < 0.05$.

and in the total ninhydrin positive substances, which are mostly free amino acids, of colonies exposed to 0.100 and 0.500 ml l^{-1} drilling mud for 24 h. He observed some zooxanthellae loss at 0.100 ml l^{-1} and a total loss of algae at 0.500 ml l^{-1}.

S. Prassad (personal communication) has found that treatment with 0.010 and 0.100 ml l^{-1} drill mud inhibits protein synthesis in Madracis decactis corals. Protein synthesis is a key to life activity and was measured by evaluating incorporation of titrated methionine into tetrachloracetic acid precipitable protein.

2.6 Mortality

The ultimate detrimental effect of any pollutant is the death of the organism under question. Although 96-h LC_{50}, the concentration of effluent at which 50% of test animals die after 96 hours, studies have not been conducted with corals per se, there are reports of coral mortality in many of the preceeding studies. As previously discussed, Thompson (1979) found that corals die if buried in drilling mud, or if thick layers of some types of mud are applied to their surface. Thicknesses of the layers used were not specified.

Exposure to suspended mud can also cause mortality at certain concentrations. Thompson (1980) reported 100% mortality in M. annularis in 75 h, A. cervicornis in 52 h, and A. agaricites in 65 h exposed to 1.00 ml l^{-1} drilling mud, but no lethal effects at 0.316 ml l^{-1} for 96 hours. E. Powell (personal

communication) found 100% mortality in A. cervicornis exposed to 0.500 ml l^{-1} for 24 h, but no mortality at 0.100 ml l^{-1} for the same duration. Krone and Biggs (1980) reported one coral out of four in each of two FCLS treatments died within the first two weeks of exposure. In the six-week exposure of Szmant-Froelich et al. (1981) the only death was among the corals in the 0.100 ml l^{-1} treatment: one out of eight experimental animals died at the end of the fifth week of exposure, and two of the three alizarin stained corals died during the sixth week (Szmant-Froelich et al. 1981; Dodge, 1982). In almost all of the above cases, death is preceeded by expulsion of the zooxanthellae and intense mucus secretion.

While sample size in each of the above studies was insufficient to demonstrate a statistically significant increase in mortality within the indicated treatments, the weight of evidence from all experiments is highly suggestive of mortality effects in concentrations of drilling mud above 0.100 ml l^{-1}, over long time periods.

Hudson et al. (1982) found a 70-90% reduction in coral cover within a 115 m by 85 m ellipse enclosing prior drilling operations at a reef off the Philippines. They attributed much of this mortality to smothering by the drilling generated cuttings pile, which has since been removed by storm action. Drilling mud associated with the cuttings may also have had a contributory effect.

3.0 ENVIRONMENTAL IMPACT OF DRILLING MUDS ON CORALS: DISCUSSION

Two important factors that determine the ultimate effect of any pollutant on an organism or ecosystem are: the sensitivity of the organism to the pollutant and the concentration and duration of exposure experienced by the organism. The past section reviewed the data available on coral sensitivities to drilling mud. It is apparent that sensitivities may vary greatly among specimens of the same species, among species, and with the batch of drilling mud tested. In general, it appears that muds containing mainly barite, bentonite, and water may be less toxic to corals than muds used later in the drilling sequence, which can contain large amounts of FCLS and other additives such as diesel fuel.

Drilling mud may be discharged in basically two ways:
1) Because drill mud is expensive, it is recirculated by introducing used drilling mud and suspended cuttings onto a shaker table. Separation is never complete and when cuttings are dumped from the platform, adhering mud washes off creating a noticable plume, while the cuttings quickly settle to the bottom. This type of discharge occurs continuously during drilling.
2) Every 3 to 7 ds during the course of a drilling operation, and especially at the end of drilling, bulk discharges of spent drilling mud occur. These discharges are typically high volume (as much as 2,000 barrels of mud in a few hours (Thompson and Bright, 1980).

Some information is available concerning the concentrations of drilling mud in the discharge plume downstream from the source. The dispersion of drilling mud components depends partially on their size and density. Most of the coarse material (cuttings) in the discharge settles very near the rig base; fine and soluble components are transported a greater distance from the source. Factors that affect transport include rate of discharge, depth of discharge, currents and wave regime at the time of discharge, the depth of the mixed layer, and the density of the discharge in relation to the density structure of the receiving waters. These factors are discussed in detail elsewhere in this volume [Chapter (Proni and Trefry); Chapter (Trefrey and Trocine); Chapter (Pierce et al.)].

It appears that in most cases cuttings accumulate within 100-200 m of the source. Depending on the depth and duration of drilling, several meters of cuttings may accumulate in piles within a few meters from the rig. Further away, several cm of finer components, particularly barite particles, which are very dense and settle out quickly, may accumulate over the bottom. Meek and Ray (1980) studied induced sedimentation, accumulation, and transport of drilling mud discharges during exploratory drilling on Tanner Bank, California. Within a 150 m radius of discharge, sediment traps collected 7-52 g m^{-2} per day, whereas a control trap outside of discharge influence only averaged

0.8 g m^{-2} per day. Calculations based on particulate composition, water depths, and currents indicated the largest cuttings would fall directly below the platform, whereas the smallest particles would settle up to 2,500 m from the source. Nevertheless, finer particles were collected in the traps than would have been expected from the theoretical calculations alone. For soft-bottom cummunities Mariani et al.(1980) conducted benthic surveys to monitor accumulation of trace elements during exploratory drilling in the mid-Atlantic Bight. They found that discharge caused some alteration in the grain-size distribution and clay mineralogy in the surface sediment, as well as alterations in trace metal content of sediment within a 3.2 km radius of the site. In addition Menzie et al. (1980) evaluated exploratory drilling at a well site at the shelf break off New Jersey. A zone of visible discharge accumulation was observed in the immediate vicinity of the well and elevated clay levels were found up to 800 m away and down current. Although these two sites may not be typical of a coral reef area, the results suggest that sedimentation effects can occur over large distances away from the source.

Discharge plumes, which can be traced by suspended solids or trace metal concentrations, are of two basic types. Those associated with cuttings discharge are of relatively low volume but long duration, while those associated with bulk discharge (to make room for new mud preparation or at the end of a drilling

operation) are usually of high volume but short duration. It has been estimated (Ayers et al., 1980; Ray and Meek, 1980; Trefrey et al. [this volume]) that plumes may last from 3 to over 12 h and may travel from 500 m to 3 km before dilution to background levels. Fig. 7 illustrates some results of Ray and Meek (1980) for discharge plumes downstream from an exploratory well offshore of California.

At low discharge rates background levels of suspended solids are reached typically within less than 100 m from the source (Ray and Meek, 1980; Shinn et al., 1981). For a bulk discharge plume (119,240 l h^{-1} Ray and Meek (1980) determined total suspended solids concentrations within the plume of 25.2 mg l^{-1} at 74 m and 4.04 mg l^{-1} at 500 m. Background levels were approached at 900 m. The mud contained a total suspended solid concentration of 250,000 mg l^{-1}. A volume conversion reveals that approximately 0.100 ml l^{-1} and 0.016 ml l^{-1} were present at 74 m and 500 m respectively. For a bulk discharge plume in the Gulf of Mexico, Shinn et al. (1981) found approximately 0.024 ml l^{-1} at 96 m (converted from 11.31 mg l^{-1} , assuming a total suspended solids concentration of the whole mud of 476. g l^{-1}).

There are obvious problems in extrapolating from experimental work on corals to concentrations <u>in situ</u> specimens might encounter at increasing distances downplume. These would be

variable in magnitude, frequency, and duration. Laboratory experiments have maintained constant exposure over set durations. An apparently critical level for drilling mud seems to be 0.100 ml l^{-1} in many of the experimental results. Even for bulk discharges, the available data suggest that field concentrations would not reach this level much beyond 100 m and then not for long time periods.

Sedimentation effects are harder to estimate but again these might be expected to be greatest within approximately 100 m of the drilling mud and cuttings source. Exact dimensions in both cases would depend upon factors already discussed, such as discharge type and volume, currents, ect., and firm predictions can not be made at this time.

4. RESEARCH NEEDS

More complete information is needed on concentrations of drilling mud and of its components at various distances downplume under various discharge and current conditions. This can be accomplished by additional monitoring studies on the ultimate short and long term fate of the materials in the marine environment. Use of existing data and new data to be obtained will be useful as input for computer modeling efforts to predict fate in coral reef areas where drilling is planned, provided the necessary oceanographic data from that site are also or can be made available. Fate modeling efforts have been initiated (e.g., Brandsma et al., 1980) and should eventually be able to provide indications of effluent fate including concentrations, distribu-

tion, and the chronic dose expected to corals and other reef biota at gradients from the proposed source.

Laboratory experiments should be designed to more nearly replicate expected exposure levels in the field. In addition previous work has not included follow-up monitoring of experimental animals to document any long-term effect. Studies are needed to assess mortality, general physiology, reproduction, and growth (extension and calcification) over long periods after drilling mud stress has been removed.

Additional field work would also be valuable to assess drilling impacts. Baseline studies to include quantitative assessment and description of a reef system (e.g., Dodge et al., 1982) before, during, and at intervals after drilling could provide important information. Such studies would only be possible with extensive cooperation from drilling companies to provide information on the reef area planned to be drilled and access during and after drilling. One of the few studies of this type to date is by Hudson et al. (1982) who evaluated a Philippine reef ocmmunity several years after drilling operations were completed.

When more data on effects are available, this may be coupled with fate information as input to effects computer models for prediction of drilling consequences in specified areas. A recent effort of this kind (Auble et al., 1981), while admittedly suffering from deficiencies of appropriate input data, provides a good example

of the usefulness of the modeling approach.

This review has concentrated on effects of drilling mud *per se* on corals. A variety of other potentially adverse impacts may result from drilling activities and deserve consideration. Multiple production drilling in a reef area may compound environmental stresses from increased drilling fluids and from physical effects such as set up and anchor and chain damage. In addition, once oil is found and produced, the possibility of spills and seeps is greatly increased. Oil pollution and oil plus dispersant effects (Loya and Rinkevich, 1980) are also important factors that need research for best management and preservation of corals and coral reefs.

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FIGURE CAPTIONS

Figure 1: The effects of 0, 0.001, 0.010, and 0.100 ml l^{-1} drilling mud on the percentage of polyps retracted in the coral Madracis decactis over a 14-d exposure period (after Thompson, 1980).

Figure 2: The retraction factor (number of polyps retracted on experimental corals multiplied by the time duration retracted, divided by the total number of polyps observed multiplied by the total time observed) of colonies of Madracis decactis exposed to various concentrations of ferrochrome lignosulfonate (FCLS) for 30 d (after Thompson, 1980).

Figure 3: Rate of (a) mean nitrate uptake; (b) respiration; (c) ammonium uptake; and (d) calcification measured for short durations at weekly intervals for colonies of Montastrea annularis exposed to various concentrations of drilling mud for six weeks. Respiration rates,measured as changes in dissolved oxygen, were determined at night. Calcification rates, measured as changes in total alkalinity, were determined under light conditions. Nutrient uptake rates, measured as changes in concentration, were determined in both light and dark. Error bars represent the 95% confidence limits.

Figure 4: Cross-section of single corallite within skeleton of Montastrea annularis. The dashed line indicates the trace of the alizarin red stain. The technical names for various

skeletal structures are indicated. Abbreviations indicate the skeletal growth and shape parameters that were measured by reference to the stain. SI = septa increase; CI = columella increase; EBI = endotheca base increase; NFL = new fossa length; OEL = old endotheca length. (after Dodge, 1982)

Figure 5: Growth parameters SI, CI, and EBI (see Fig. 4) normalized to OEL (pre-experiment endotheca length) measured on corals exposed for six weeks to treatments of 0, 0.001, 0.010, and 0.100 ml l^{-1} drilling mud. (after Dodge, 1982).

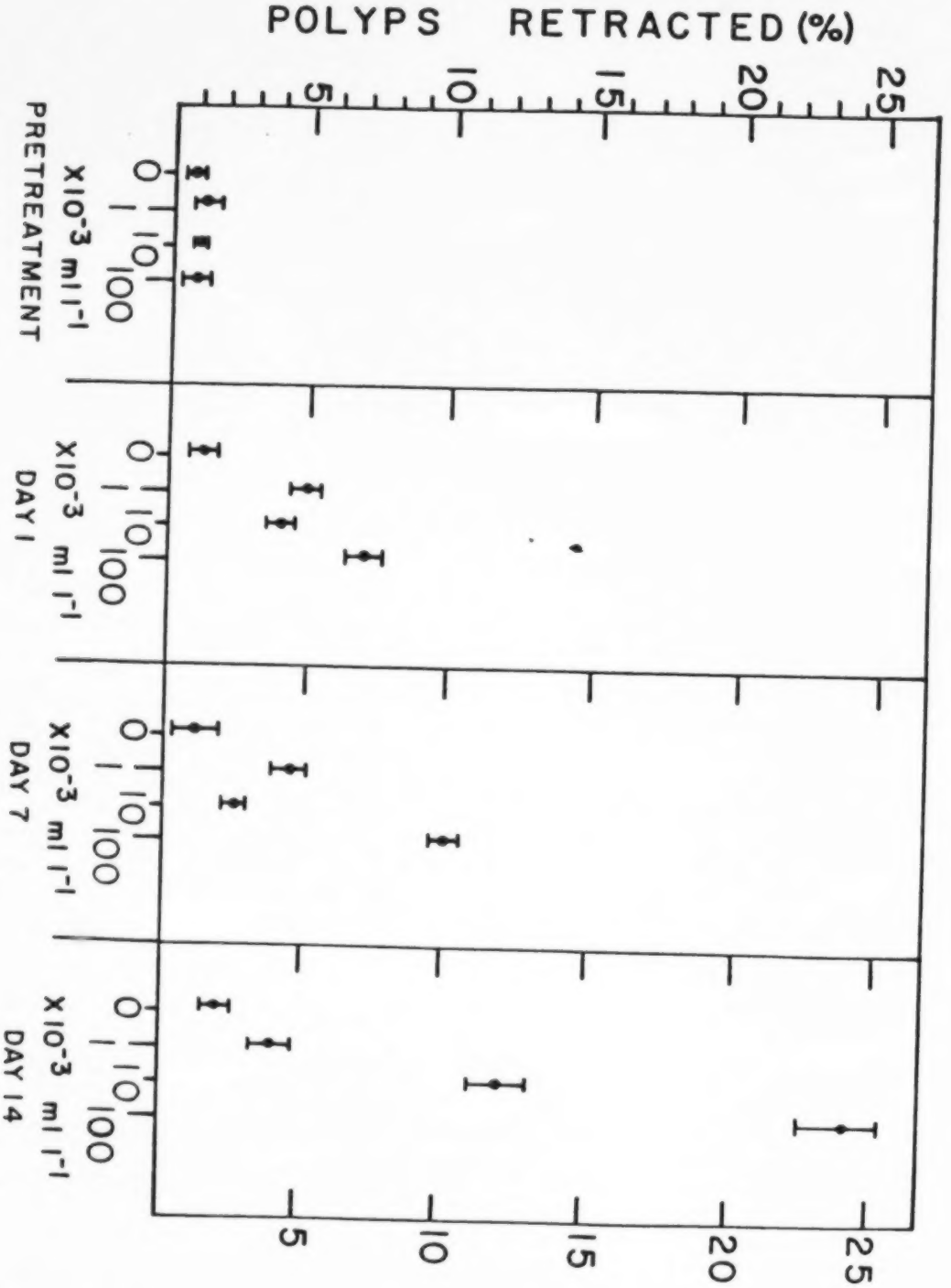
Figure 6: (upper) Average winter (Feb.-May) sea surface water temperature by year (1979-1950) in the vicinity of the Flower Gardens Banks. The data were obtined from the National Climatic Center, Asheville, North Carolina.

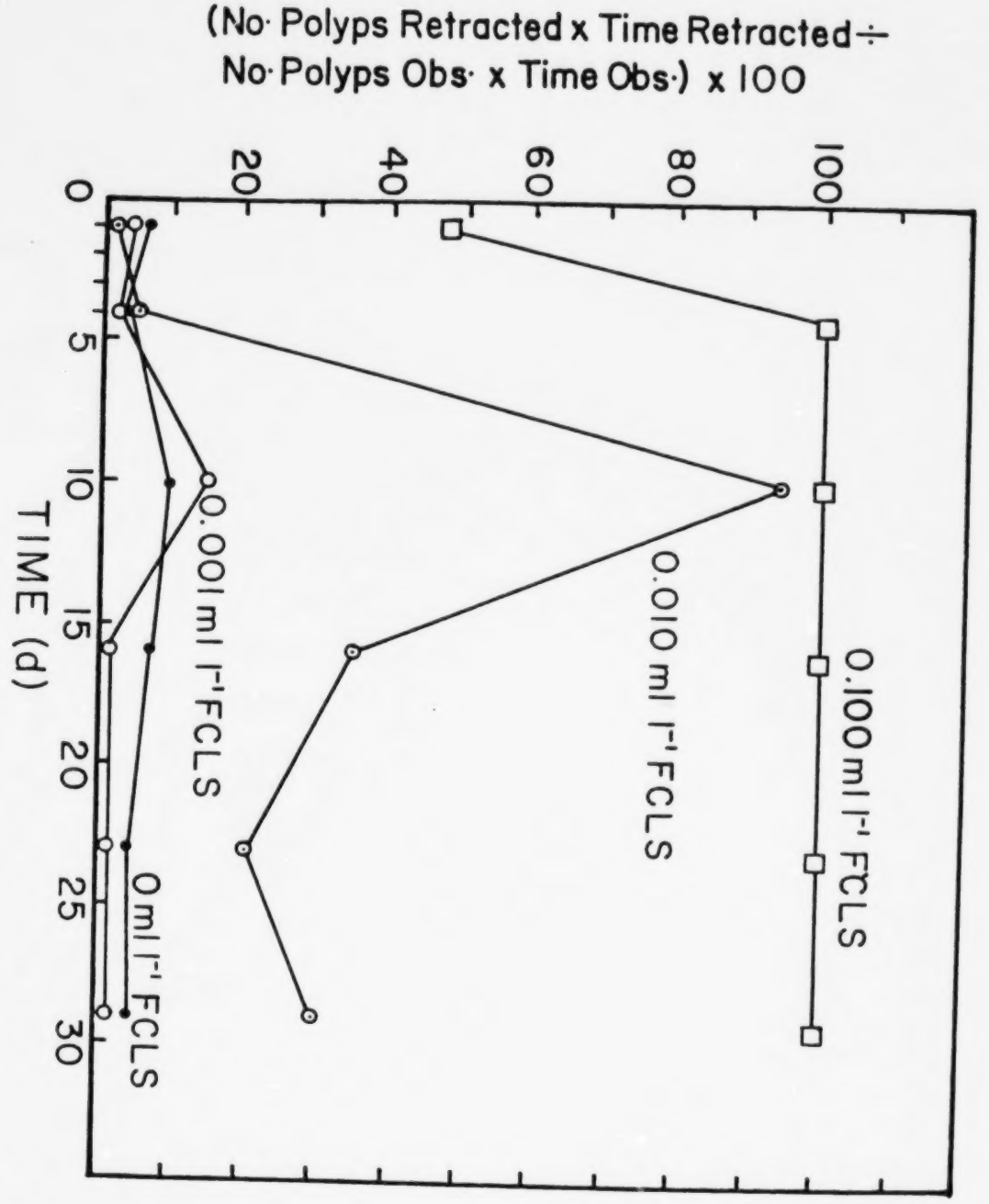
(middle) Index coral growth chronology of 12 corals (M. annularis) sampled by Hudson and Robbin (1980) at the East Flower Gardens Bands. The vertical axis is the percent of mean growth for each year (in 1979-1887) divided by 100. (after Dodge and Lang, 1983)

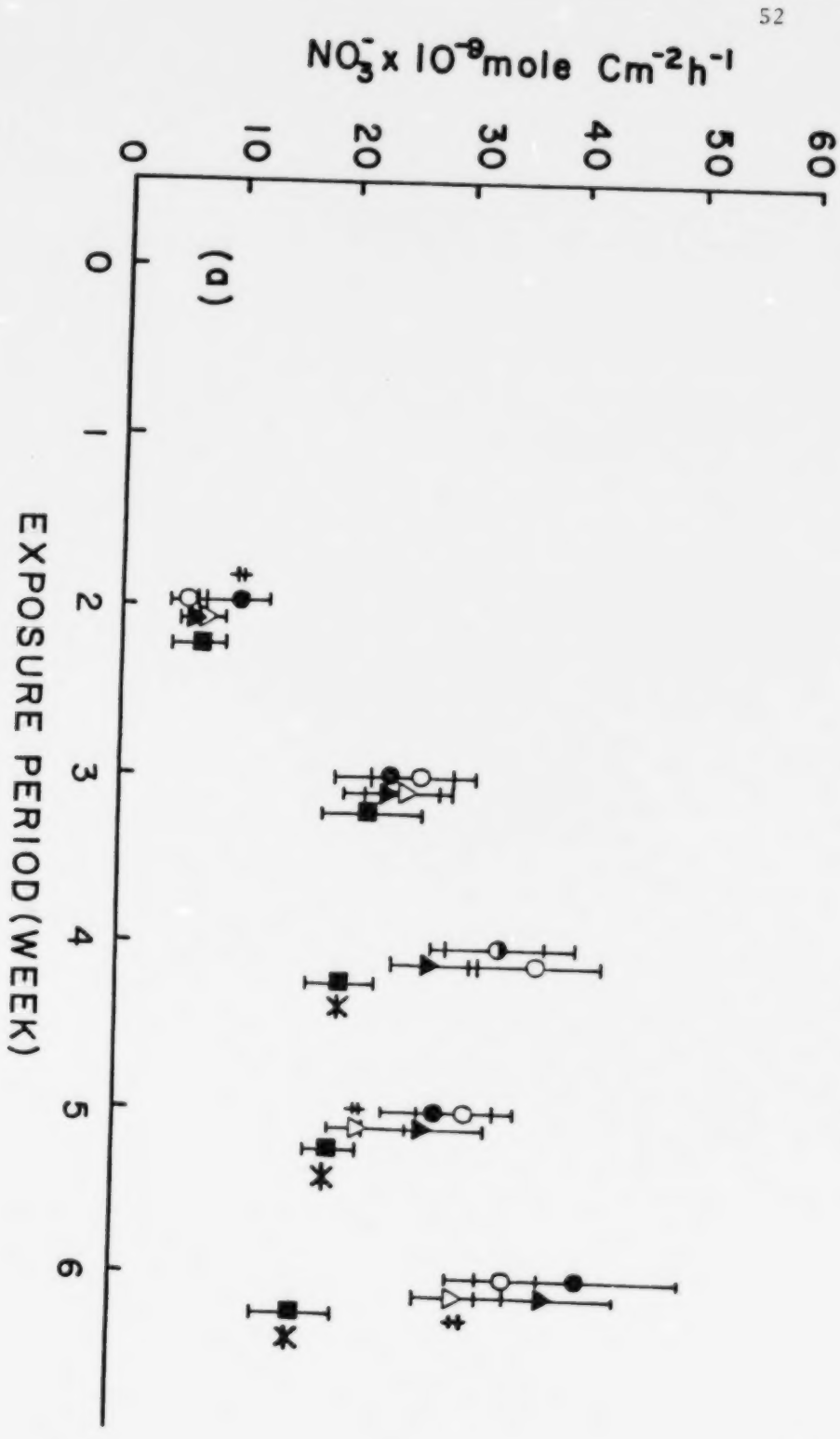
(lower) Annual average daily flow in cubic meters per second of the Atchafalaya River at the mouth from 1928-1979 (data from R. Cunningham, personal communication).

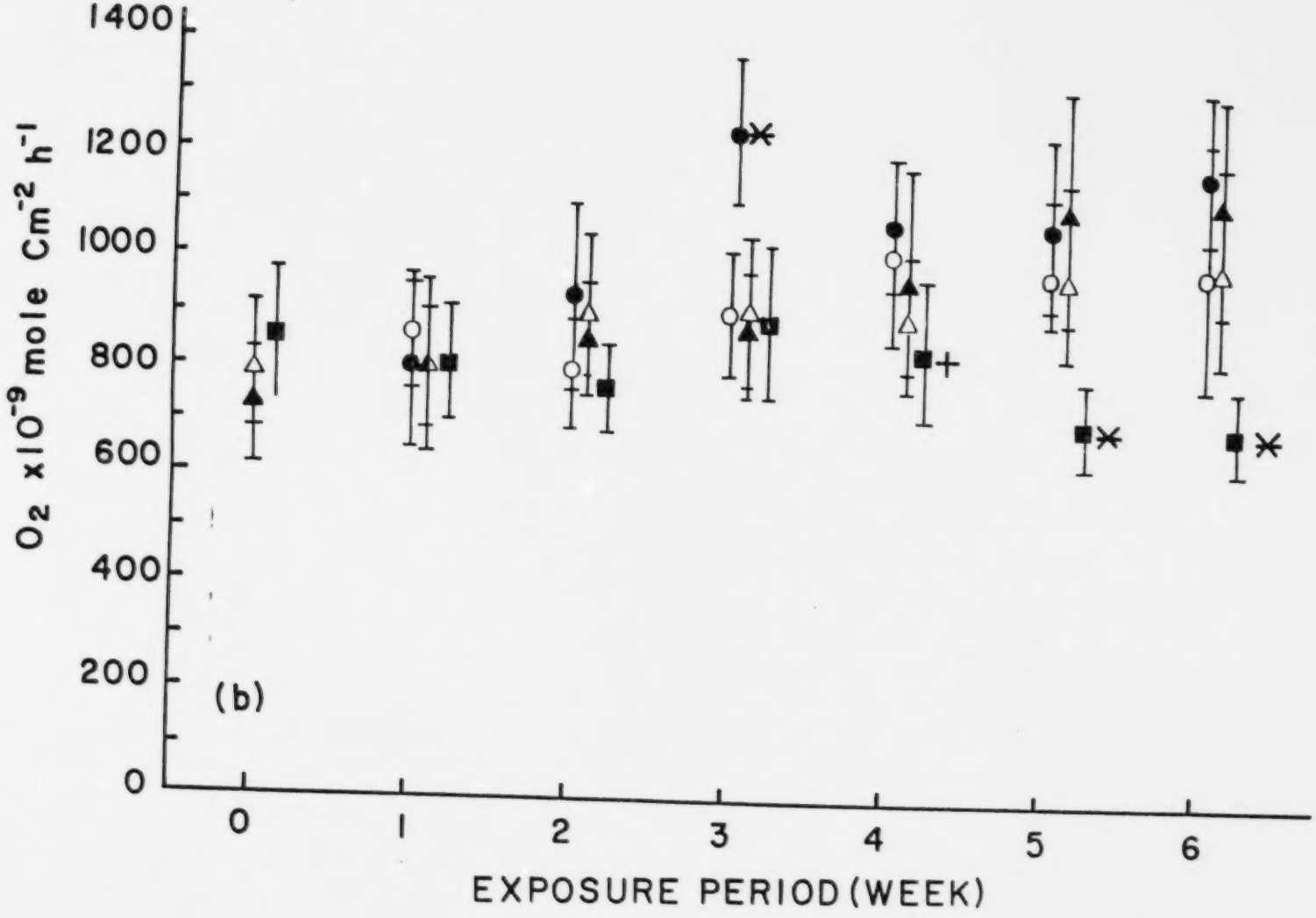
Figure 7: Percent light transmittance within 8 discharge plumes downstreme from an exploratory well on Tanner Bank, California. The open circles are from a bulk discharge of drilling mud of 119,240 l h^{-1}; the closed circles are from cuttings discharges (after Ray and Meek, 1980).

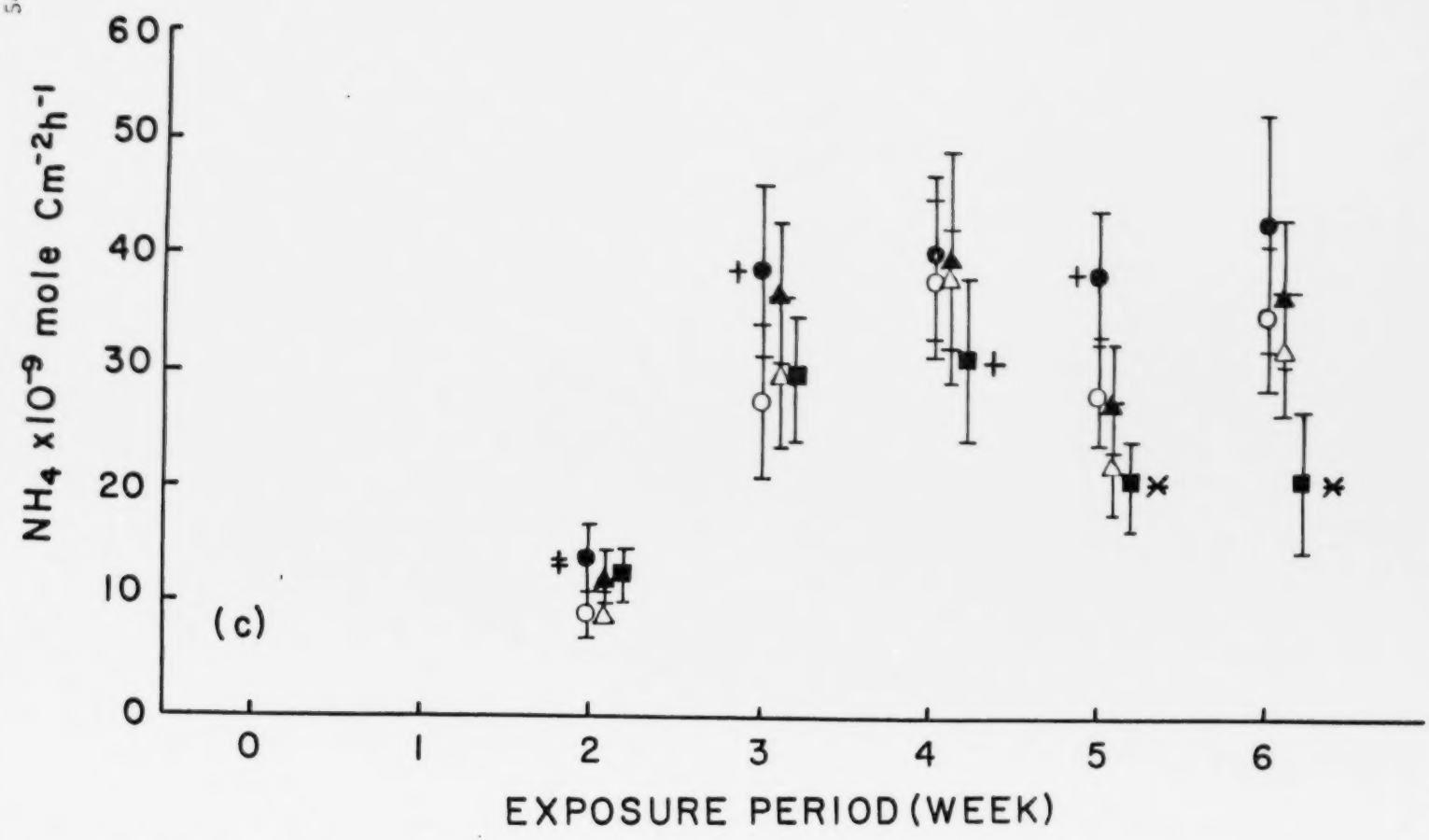
FIG. 1


POLYPS RETRACTED (%)
5
10
15
20
25
0
1
10
100
X10-3 ml l-1
PRETREATMENT
DAY 1
DAY 7
DAY 14


(No. Polyps Retracted x Time Retracted ÷
No. Polyps Obs. x Time Obs.) x 100
0
20
40
60
80
100
0
5
10
15
20
25
30
TIME (d)
0.001 ml l⁻¹ FCLS
0.010 ml l⁻¹ FCLS
0.100 ml l⁻¹ FCLS
0 ml l⁻¹ FCLS


$NO_3^- \times 10^{-9}$ mole $Cm^{-2}h^{-1}$
0
10
20
30
40
50
60
(a)
0
1
2
3
4
5
6
EXPOSURE PERIOD (WEEK)


1400
1200
1000
800
600
400
200
0
O_2 x10^{-9} mole Cm^{-2} h^{-1}
(b)
0
1
2
3
4
5
6
EXPOSURE PERIOD (WEEK)


60
50
40
30
20
10
0
$NH_4 \times 10^{-9}$ mole $Cm^{-2}h^{-1}$
(c)
0
1
2
3
4
5
6
EXPOSURE PERIOD (WEEK)

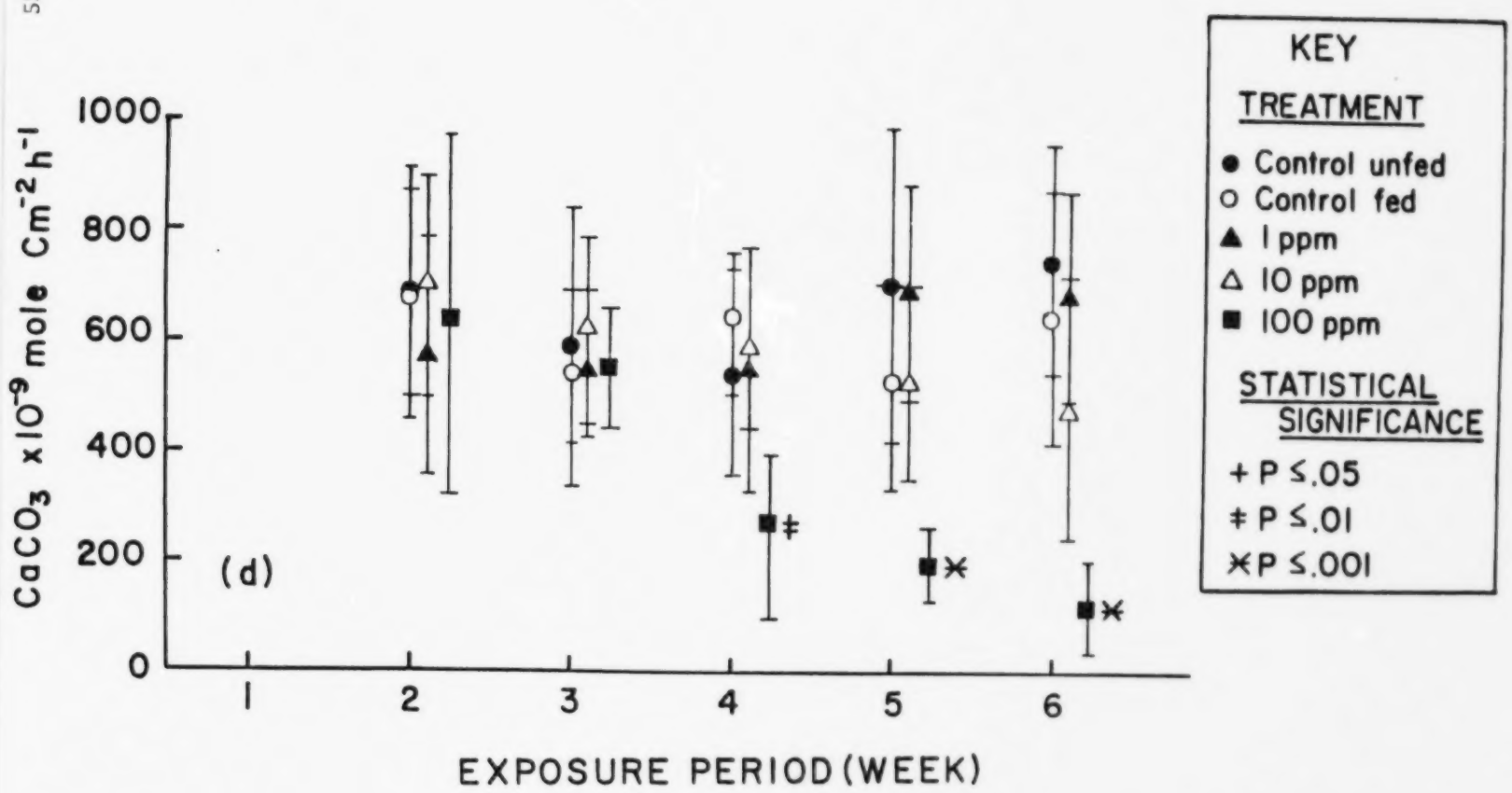
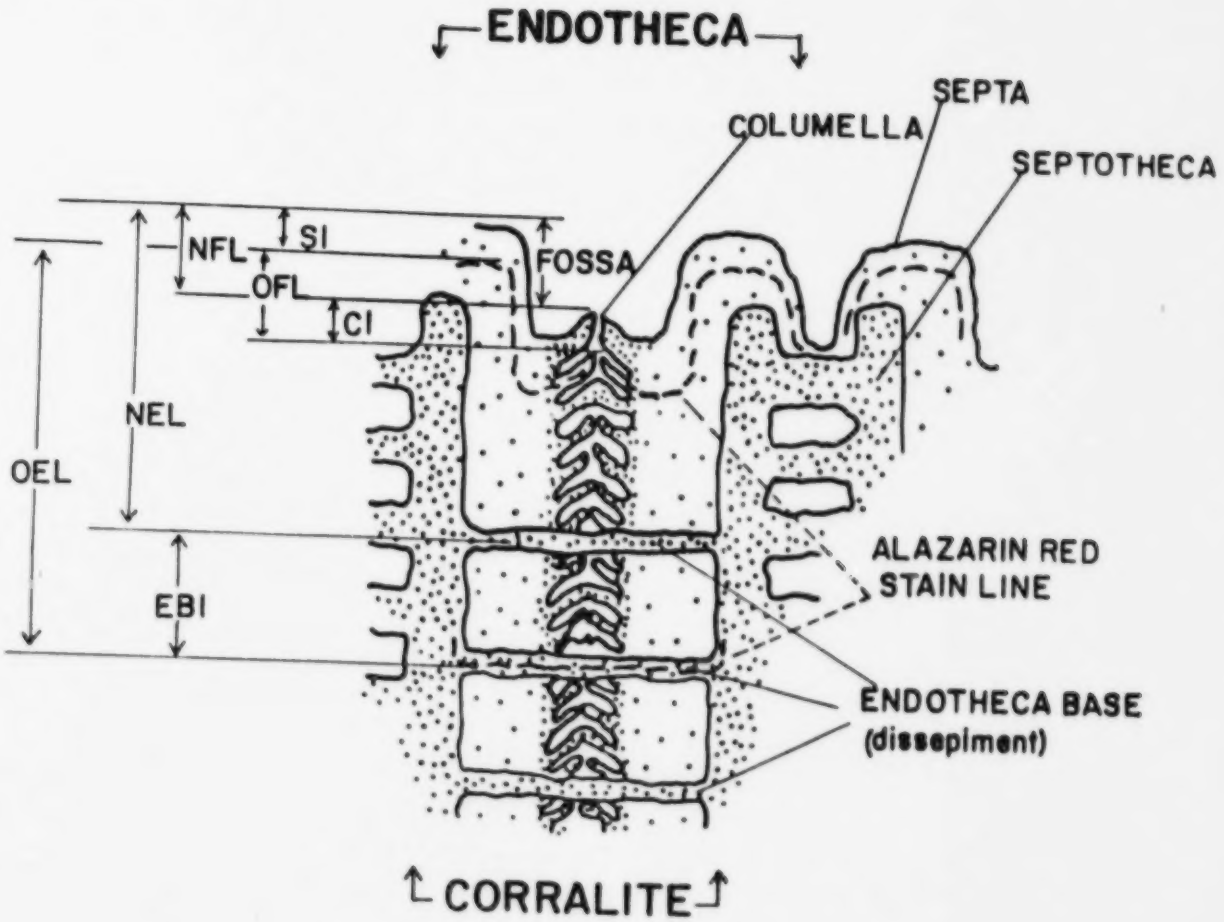
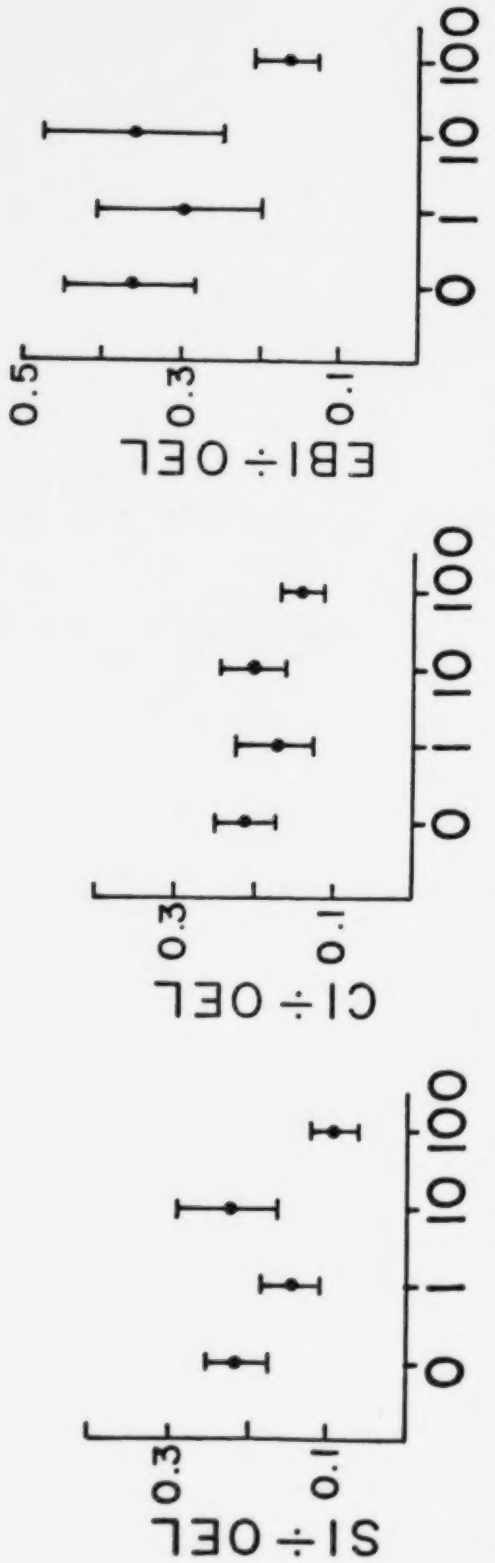
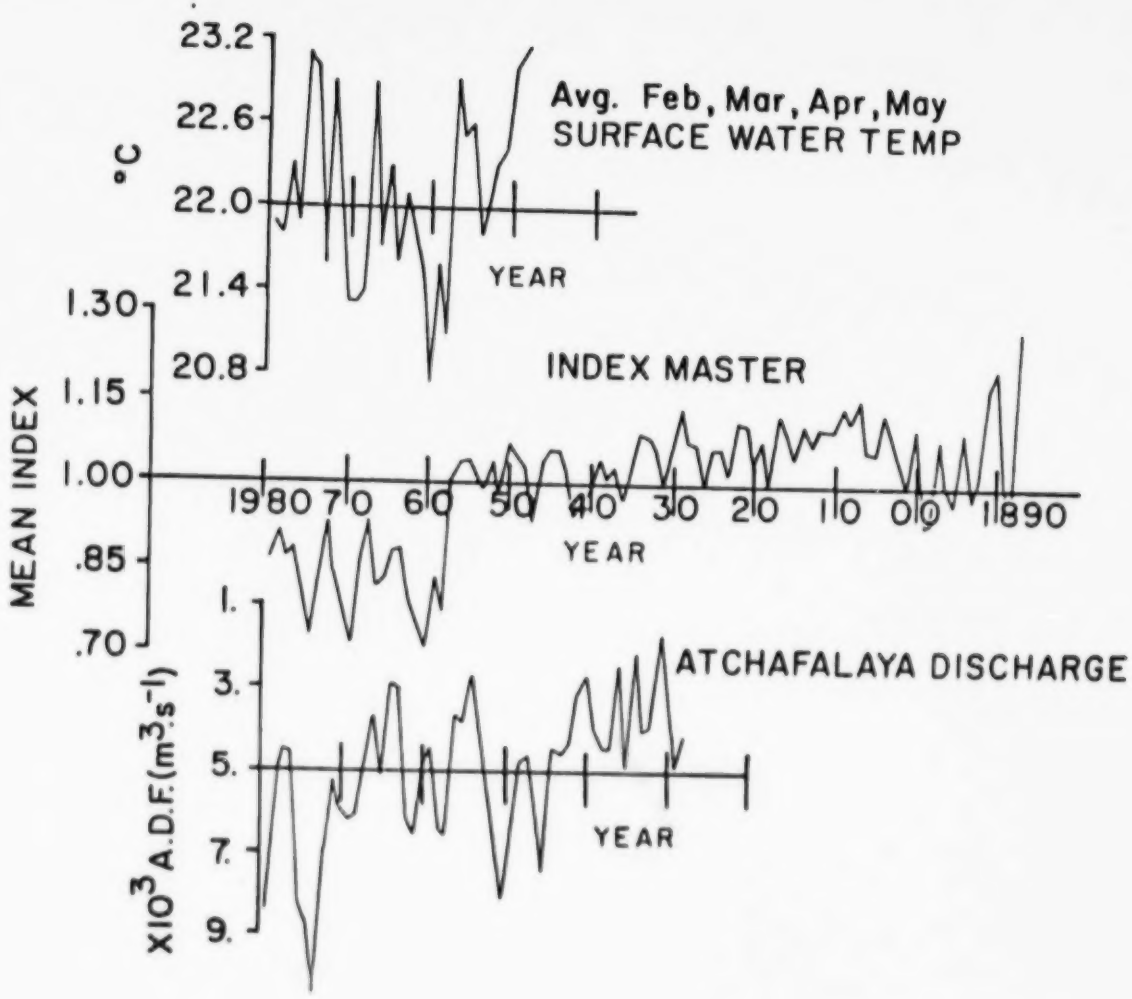

1000
800
600
400
200
0
$CaCO_3$ x 10^{-9} mole Cm^{-2} h^{-1}
(d)
1
2
3
4
5
6
EXPOSURE PERIOD (WEEK)
KEY
TREATMENT
● Control unfed
○ Control fed
▲ 1 ppm
△ 10 ppm
■ 100 ppm
STATISTICAL SIGNIFICANCE
+ P ≤ .05
‡ P ≤ .01
✳ P ≤ .001

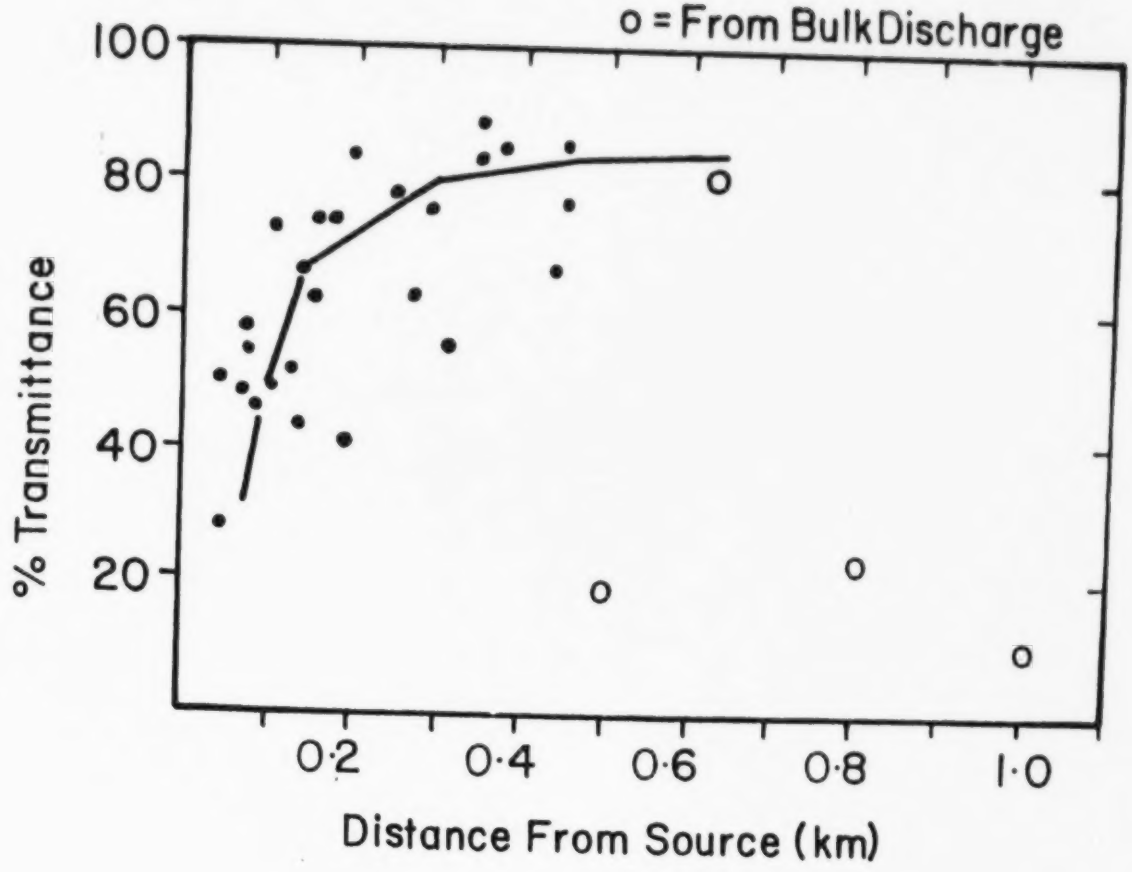
FIG.

56


ENDOTHECA
SEPTA
COLUMELLA
SEPTOTHECA
NFL
SI
FOSSA
OFL
CI
NEL
OEL
EBI
ALAZARIN RED
STAIN LINE
ENDOTHECA BASE
(dissepiment)
CORRALITE


SI÷OEL
CI÷OEL
EBI÷OEL
0.5
0.3
0.1
0
1
10
100
TREATMENT (X10⁻³ ml l⁻¹)


23.2
22.6
22.0
21.4
20.8
°C
Avg. Feb, Mar, Apr, May
SURFACE WATER TEMP
YEAR
1.30
1.15
1.00
.85
.70
MEAN INDEX
INDEX MASTER
1980 70 60 50 40 30 20 10 09 1890
YEAR
1.
3.
5.
7.
9.
X10³A.D.F.(m³s⁻¹)
ATCHAFALAYA DISCHARGE
YEAR


o = From Bulk Discharge
100
80
60
40
20
% Transmittance
0·2
0·4
0·6
0·8
1·0
Distance From Source (km)